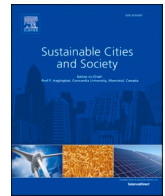




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# Riding the wave: Predicting the use of the bike-sharing system in Barcelona before and during COVID-19

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## ABSTRACT

To simultaneously promote health, economic, and environmental sustainability, a number of cities worldwide have established bike-sharing systems (BSS) that complement the conventional public transport systems. As the rapid spread of COVID-19 becoming a global pandemic disrupted urban mobility due to government-imposed lockdowns and the heightened fear of infection in crowded spaces, populations were increasingly less likely to use public transportation and instead shifted toward alternative transport systems, including BSS. In this study, we use probabilistic machine learning in a quasi-experimental research design to identify how the relevance of a comprehensive set of factors to predict the use of Bicing (the BSS in Barcelona) may have changed as COVID-19 unfolded. We unpack the key factors in predicting the use of Bicing, uncovering evidence of increasing bike-related built infrastructure (e.g., tactical urbanism), trip distance, and the income levels of neighborhoods as the most relevant predictors. Moreover, we find that the relevance of the factors in predicting Bicing usage has generally decreased during the global pandemic, suggesting altered societal behavior. Our study enhances the understanding of BSS and societal behavior, which can have important implications for developing resilient programs for cities to adopt sustainable practices through transport policy, infrastructure planning, and urban development.

## 1. Introduction

Bike-sharing systems (BSS) refer to a “service that makes bikes available for shared use on a short-term basis” (Hu, Zhang, Lamb, Zhang, & Jia, 2019: 1). They involve a set of bikes distributed within a city so that users can take and leave one without the responsibility or cost of ownership (Fishman, 2016). In dense urban areas, BSS have become a prevalent mode of mobility to complement conventional public transport systems by covering short trips to destinations that are distant from bus, metro, and train routes (e.g., Bauman, Crane, Drayton & Titze, 2017; Hu & Liu, 2014; Lu, Hsu, Chen & Lee, 2018; Shaheen, Guzman & Zhang, 2010). Since their emergence in Amsterdam (i.e., White Bikes in 1965) and subsequent revival in Copenhagen (i.e., Nakskov in 1993), the prevalence of BSS has intensified over the years, growing to about 2000 active systems operating in numerous cities in 85 countries worldwide (see <https://bikesharingworldmap.com>). These systems are largely concentrated in China, Europe, and North America (Shaheen et al., 2010). BSS operate by allowing users to pick up bikes and return

them to many docking stations distributed across a city (docked BSS) or to take readily available bikes using a mobile application and leave them within a system’s operational area (dockless BSS). The primary goal of BSS is to simultaneously promote health, economic, and environmental sustainability by encouraging active mobility to improve the levels of physical fitness of an urban population, generating journey time-savings for commuters, and reducing external social costs such as pollution, greenhouse gas emissions, noise, and traffic congestion in cities (Bullock, Brereton & Bailey, 2017).

As the rapid spread of the coronavirus disease (COVID-19) becoming a global pandemic disrupted urban mobility due to government-imposed lockdowns and the heightened fear of infection in crowded spaces, BSS have gained significant attention by serving as an alternative form of transport for city residents who preferred to avoid using other means of public transportation (Pase, Chiariotti, Zanella & Zorzi, 2020). For example, the Spanish National Institute of Statistics reports a significant drop (an average of 46%) in the monthly usage of metros and buses in Barcelona from 2019 to 2020 (excluding the government-imposed

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lockdown period), whereas the use of BSS in the city has increased over the same period. In a similar vein, New York city commuters increased their use of BSS in preference to the subway during the global pandemic (Teixeira & Lopes, 2020). This shift in the mobility behavior of urban commuters as the global pandemic unfolded demonstrates how BSS have developed into a more robust and resilient mobility option than other transport modes such as metros, taxis, and buses (Hu, Xiong, Liu & Zhang, 2021; Pase et al., 2020; Wang & Noland, 2021). As a response to the disruption to mobility and taking advantage of the lockdowns during the global pandemic, several cities worldwide (e.g., Barcelona, Cape Town, Nairobi, Oslo, Paris, Toronto, and Vancouver) have engaged in tactical urbanism (c.f., Lydon & Garcia, 2015)—a temporary low-cost initiative to rapidly change urban environments (Graziano, 2021)—to transform streets so that pedestrians and cyclists can enjoy public spaces without the fear of contagion (Buehler & Pucher, 2021).

Despite the growing research interest on a number of factors that influence the use of BSS (see the reviews of Eren & Uz, 2020; Fishman, Washington & Haworth, 2013; Si, Shi, Wu, Chen & Zhao, 2019), we still lack a full understanding of how an exogenous shock such as the global pandemic may have altered how such factors (including tactical urbanism) can predict BSS usage. The extant research regarding the impact of COVID-19 on BSS largely investigates the factors influencing the increase or decrease in bike-sharing ridership (e.g., Jobe & Griffin, 2021; Teixeira & Lopes, 2020), changes in the demand for BSS during the global pandemic (e.g., Chibwe, Heydari, Imani & Scurtu, 2021; Teixeira, Silva & Moura e Sá, 2021), and the movement trajectories of the users (e.g., Hu et al., 2021; Shang et al., 2021). To the best of our knowledge, only a handful of studies have examined how the effect of factors that predict BSS ridership may have changed as COVID-19 unfolded (e.g., Hong, McArthur, Sim & Kim, 2022; Teixeira et al., 2021). Thus, in this study, we answer the following research questions: what are the relevant factors that help us predict the use of BSS and how has COVID-19 affected the relevance of these factors?

The importance of answering our research questions is two-fold. First, our study addresses the calls for research to capture a more complete picture of the factors related to BSS and its users (c.f., Eren & Uz, 2020; Willberg, Salonen & Toivonen, 2021). We use probabilistic machine learning in a quasi-experimental research design to analyze a large dataset comprising several types of information—including origin-destination user-trip data, built infrastructure for cycling, topological properties of the city, census, tax filing, cadastral records, and weather station reports—which allow us to not only identify the physical conditions influencing BSS usage, but also to unpack the profiles and behavioral patterns of the users. Our findings can help policy makers in developing programs that promote active mobility and implement sustainable practices through transport policy, infrastructure planning, and urban development.

Second, our focus on COVID-19 highlights the importance of considering highly disruptive events in urban planning and management (c.f., Sharifi & Khavarian-Garmsir, 2020). In this study, we demonstrate how societal behavior is altered by an exogeneous shock that immediately affects the operations of public transport systems, including bike sharing (e.g., Saberi, Ghamami, Gu, Shojaei & Fishman, 2018; Teixeira & Lopes, 2020). The results show that not all the factors included in our analysis are relevant in predicting Bicing usage before and during the global pandemic and that the relevance of the factors to predict Bicing usage has generally decreased after the lockdown period. Our research can be useful for understanding the impact of disruptive events on the mobility of urban communities and for the preparations, management, and resilience of cities with respect to future disruptive events.

This paper is structured as follows. We first review the literature on how COVID-19 affected the use of BSS and how tactical urbanism emerged as a response of cities to mitigate the effect of the global pandemic on the mobility behavior of urban communities. We then describe our research methods by expounding on our research case study, empirical data, and analytical technique. Next, we present our

findings and relate our results to previous studies on BSS. We conclude with a discussion on the study's research and practical implications, limitations, and suggested avenues for future research.

## 2. Background literature

### 2.1. Bike-sharing systems during COVID-19

As COVID-19 disrupted urban mobility worldwide, academic interest on the effects of the global pandemic on BSS also saw a noticeably increase. By analyzing user-trip data in various cities (e.g., Beijing, Budapest, Chicago, Lisbon, Nanjing, and New York), a large body of research focuses on the changes in BSS ridership, thereby providing evidence of a drastic decrease in BSS usage due to the stringent measures (i.e., lockdowns) taken worldwide to contain the virus (e.g., Albuquerque, Andrade, Ferreira, Dias & Bacao, 2021; Bucsky, 2020; Hu & Chen, 2021; Hua, Chen, Cheng & Chen, 2021; Shang et al., 2021; Teixeira & Lopes, 2020). In fact, given the high transmission rate of COVID-19 and that lockdowns limit human contact at scale (Melnick & Ioannidis, 2020), several studies show how the widespread lockdowns have effectively mitigated the spread of the virus (e.g., Alfano & Ercolano, 2020; Amer, Hammoud, Farran, Boncz & Endrei, 2021; Ibarra-Vega, 2020; Kharroubi & Saleh, 2020; Lau et al., 2020).

However, despite the decline in BSS usage during the global pandemic, scholars have also found evidence of a rebound (Li, Zhang, Zhu & Ren, 2021), which can be attributed to a post-lockdown increase in demand for BSS as a substitute for conventional public transportation systems (e.g., Chibwe et al., 2021; Heydari, Konstantinoudis & Behsoodi, 2021; Teixeira et al., 2021; Wang & Noland, 2021). Interestingly, BSS have emerged as a more resilient mobility mode in urban communities than other forms of transit, even surpassing walking and driving (e.g., Hu et al., 2021; Nikiforiadis, Ayfantopoulou & Stamelou, 2020). In the face of mounting concerns regarding the low likelihood of travel behavior returning to pre-pandemic levels because of the perceived risk of exposure to the virus (c.f., Currie, Jain & Aston, 2021; Dingil & Esztergár-Kiss, 2021; Shamshiripour, Rahimi, Shabanpour & Mohammadian, 2020), previous studies reveal that the use of BSS in many cities have already reached, or even surpassed, pre-pandemic levels (e.g., Kubalák, Kalašová & Hájník, 2021; Song, Zhang, Qin & Ramli, 2022; Wang & Noland, 2021). Moreover, the average BSS trip duration and/or distance traveled in several large cities (e.g., Boston, Chicago, London, and New York) has increased during the pandemic, likely because of the overall reduction in transportation services and the tendency of urban populations to avoid close contact with others in the crowded spaces of public transport (Hu et al., 2021; Li, Zhao, Haitao, Mansourian & Axhausen, 2021; Padmanabhan et al., 2021; Teixeira et al., 2021; Teixeira & Lopes, 2020).

The resilience of BSS during COVID-19 can be attributed to the altered mobility behavior of urban communities. By analyzing the spatiotemporal distribution of BSS trips, several studies show that the mobility patterns of BSS users within cities have evidently shifted. For example, although researchers find that BSS movement in office areas substantially declined during the global pandemic (e.g., Chibwe et al., 2021; Shang et al., 2021), it persisted—and sometimes increased—in residential and open areas through both the peri- and post-lockdown periods (e.g., Chai, Guo, Xiao & Jiang, 2021; Hu et al., 2021; Li et al., 2021). Similarly, although the use of BSS is more prevalent during weekdays than weekends or holidays, because bike sharing is largely used for work-related activities (e.g., Cerutti, Martins, Macke & Sarate, 2019; Ricci, 2015; Shaheen et al., 2010), BSS usage has also increased during the nonworking days of the pandemic period (Albuquerque et al., 2021). This trend is likely due to the increase in exercise/leisure-related activities to enjoy open spaces to compensate for the fact that populations were locked down for several months (Hu et al., 2021; Kim, 2021).

The changes in mobility patterns of BSS as the global pandemic

advanced also vary depending on several socio-demographic factors that may explain the behaviors and preferences of the users. For instance, even though men tend to use BSS more than women (e.g., Fishman, 2016; Ricci, 2015; Shaer, Rezaei & Moghani Rahimi, 2021), the onset of COVID-19 prompted an increase in BSS ridership by women (Dingil & Esztergár-Kiss, 2021; Teixeira et al., 2021), possibly because their higher perception of risk than men when traveling during the global pandemic (c.f., Elias, Albert & Shiftan, 2013). The likelihood of using a BSS during the global pandemic is also greater for commuters with a higher level of education (Nikiforiadis et al., 2020), belonging to the upper income range (Bergantino, Intini & Tangari, 2021), and who are relatively older (Hua et al., 2021). These disparities when it comes to BSS ridership may be due to COVID-19 exacerbating the socio-demographic barriers for marginalized groups that lack the capacity, motivation, and/or incentive to use bike-sharing services (Teixeira et al., 2021). The extant literature shows that the effects of several socio-demographic factors (e.g., age, education, and income levels) on BSS usage before the pandemic seem to carry over after the lockdown period (c.f., Eren & Uz, 2020; Fishman, Washington, Haworth & Watson, 2015).

## 2.2. Tactical urbanism and bike-sharing systems during COVID-19

Recognizing the public's heightened concerns about COVID-19 contagion and taking advantage of the lockdowns, cities all over the world initiated rapid responses to the drastic effect of the global pandemic on urban mobility, particularly in terms of implementing programs related to bike sharing (Jobe & Griffin, 2021). These programs included reducing fees, making the use of BSS free for their users, and expanding the coverage of their systems (e.g., Hamidi & Pollackporter, 2020; Miketa & Sun, 2020). As BSS emerged as an important alternative transport mode for urban commuters (Teixera & Lopes, 2020), several cities also engaged in tactical urbanism—a temporary low-cost initiative to rapidly change urban environments (Graziano, 2021)—, aimed at providing fast but provisional solutions that may pave way for future permanent changes (c.f., Silva, 2016). Such initiatives involved converting streets that were previously dominated by traffic into open spaces for pedestrians and cyclists to enjoy, thus encouraging micro-mobility in cities and allowing BSS to thrive during the global pandemic (Torrisi, Ignaccolo, Inturri, Tesoriere & Campisi, 2021).

The rise of tactical urbanism during the global pandemic was influenced by evidence in the extant literature regarding the positive relationship between built infrastructure and cycling (e.g., Etminani-Ghasrodashti, Paydar & Ardeshiri, 2018; Moudon et al., 2005; Yang, Wu, Zhou, Gou & Lu, 2019). In fact, during the lockdowns, many cities implemented low-cost and rapid interventions throughout their urban landscape. For example, Bogotá increased the number of bike lanes using traffic cones (Miketa & Sun, 2020); New York closed down parts of its road network to allow cyclists to freely move around the city (Jobe & Griffin, 2021; Nikitas, Tsigdinos, Karolemeas, Kourmpa & Bakogiannis, 2021); and Barcelona converted several streets into pedestrian and bike-friendly spaces (Ajuntament de Barcelona, 2020). To assess the effectiveness of tactical urbanism, Kraus and Koch (2021) scraped daily bike counts in 109 European cities and found that the changes in the built environment resulted in a highly significant increase in cycling. Therefore, it is not surprising that the increase in bike-related built infrastructure during the global pandemic is also associated with an increase in BSS ridership (e.g., Bergantino et al., 2021; Chibwe et al., 2021; Pase et al., 2020).

In sum, there is a rich vein of scholarship regarding the influence of a number of factors on BSS (Eren & Uz, 2020; Fishman et al., 2013; Si et al., 2019), and our review of the literature uncovers that a growing number of studies has already embarked on trying to understand how such factors also affected BSS during the global pandemic. Previous research also provides evidence suggesting that many of these factors have had a significant effect on BSS usage throughout pre- and peri-COVID times. These factors include trip characteristics (i.e., distance

and duration), built infrastructure, weather, the socio-demographic profiles of the users, and land use.

However, to the best of our knowledge, very few studies have explored whether the influence of such factors, including the implementation of tactical urbanism to increase bike-related built infrastructure, is relevant to predict the use of BSS and how the relevance of these factors has changed over time. For instance, Hong et al. (2022) find that pollution in Seoul had a significant negative relationship on bike sharing before the global pandemic, but the association—albeit negative—has become insignificant with the onset of COVID-19. Similarly, Teixeira et al. (2021) identify that a motivational shift has taken place for the usage of BSS before and during the global pandemic. They find that BSS service coverage and quality, along with personal interests and well-being, were the primary motivators before COVID-19, whereas avoiding public transportation and social pressures also became important motivators for BSS usage as the global pandemic unfolded. Thus, this research gap gives our study the opportunity to contribute to the literature by unpacking how a comprehensive set of factors is relevant in predicting the use of BSS and determining how the impact of an exogenous event like the global pandemic may have altered the relevance of such factors.

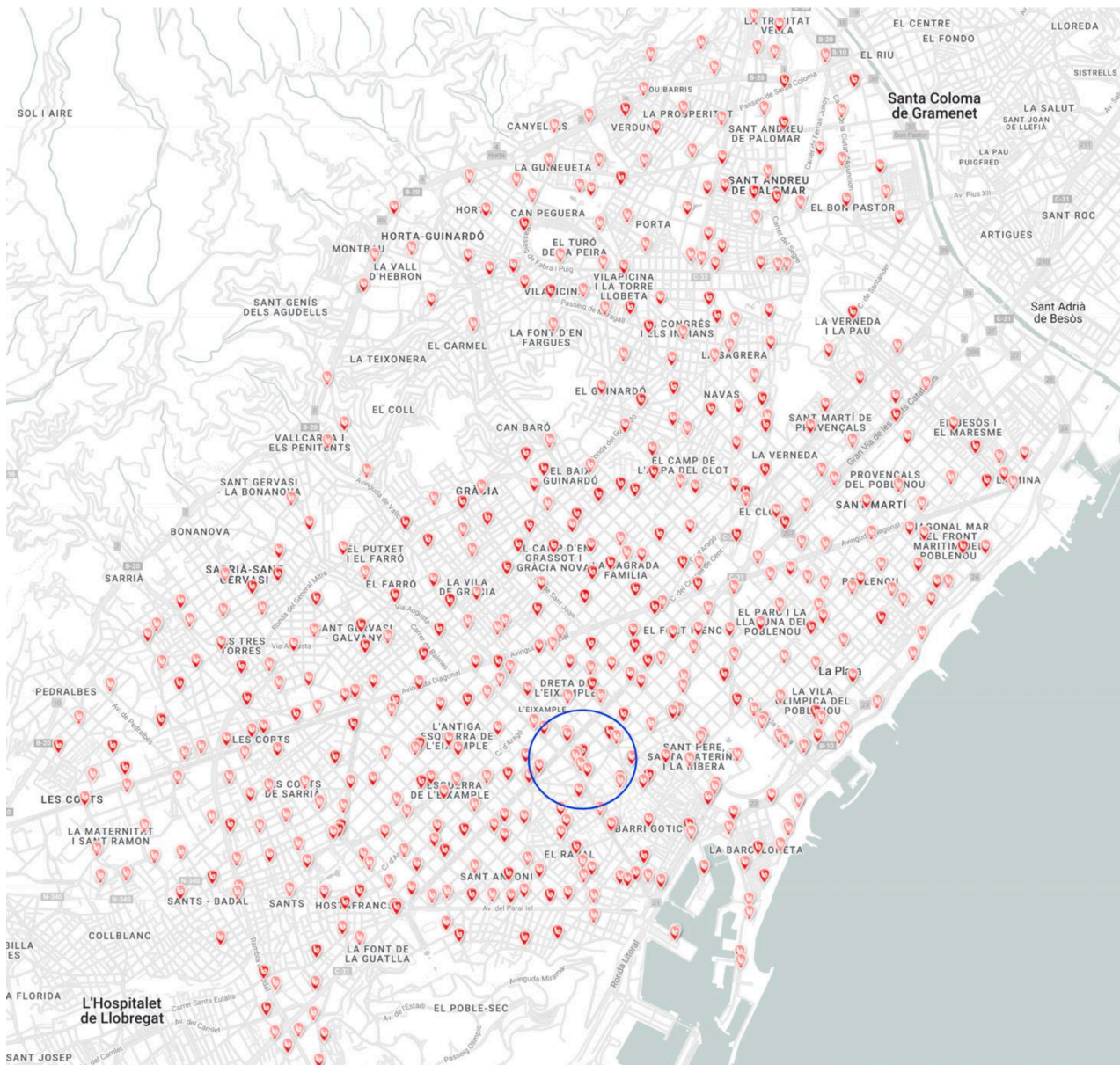
## 3. Methods

### 3.1. Case study

Our study focuses on Bicing, a docked BSS that is exclusively for the residents of Barcelona. Bicing has expanded over the years to more than 500 docking stations with approximately 7000 operating bicycles that cater to roughly 130,000 users (see <http://bicing.barcelona>). Fig. 1 shows how the river Besòs creates a natural boundary for the reach of the Bicing stations at the northeastern part of the city. Similarly, the steep increase in elevation along the Collserola Natural Park traversing from the north to the northwest of the city, and the Montjuïc hill at the southern zone also set perimeters for Bicing's operational area. The limit of Bicing's coverage to the southwest of the city is the border shared with another municipality (l'Hospitalet de Llobregat).

Bicing offers two types of bikes: mechanical and electric. Using the bikes is charged with a minimal fee for every 30 min. The use of mechanical bikes is free for the first 30 min for those users holding the *Tarifa Plana*, which is a subscription plan for high-consumption users with a fixed annual fee of 50 euros. For occasional users, the fixed annual fee is set at 35 euros with a *Tarifa de Pagament per ús*. The use of electric bikes is immediately chargeable from the start of the trip, regardless of the subscription plan. The use of any bike beyond a total of two hours is penalized with a higher fee.

We believe that our focus on Barcelona is suitable for our study of BSSs for two reasons. First, Bicing is the only docked BSS within the city limits and other BSS (i.e., dockless BSS such Bolt, Cooltra, and Yego) were not fully operational until the city government granted licenses in the latter months of 2020 (Bach, 2021). Thus, we can mitigate the possible effect of any immediate BSS substitution of Bicing when analyzing the factors influencing the use of BSS during the period covered by this study. Second, Barcelona is one of the most prominent global cities aiming to become more sustainable. To do so, it has developed several programs to support a mobility plan that promotes active mobility and reduces traffic flows within the city. Taking advantage of the disruption to transport (both public and private) during the global pandemic, the city used tactical urbanism to complement its mobility plan by implementing efficient and sustainable initiatives (i.e., street transformation and the creation of traffic-free superblocks) through several infrastructural changes—such as increasing the number of bike lanes and bike-friendly (or cyclable) streets—to accommodate the increase in the demand for bike usage (c.f., Ajuntament de Barcelona, 2020). Therefore, exploring how the BSS in Barcelona evolved during COVID-19 may offer a better understanding of the role of BSS in



**Fig. 1.** Locations of Bicing stations in the neighborhoods and districts of Barcelona.  
 Note: Circle in the map shows Plaça Catalunya, which is the center of Barcelona.  
 Source: <http://bicing.barcelona>.

the micro-mobility behavior and transport preferences of an urban community as the global pandemic unfolded.

### 3.2. Data

Our study used data from multiple sources (see Table 1 for a summary of the sources of variables). First, we worked on all Bicing-user trips that occurred between one station and another from January 1, 2019 to December 31, 2020. The system operator of Bicing (Barcelona de Serveis Municipals, S.A.) provided the more than 21.5 million origin-destination user-trip data that contained the origin station, destination station, and the start and end times of the trips. User data was not provided to avoid compromising privacy.

The trip data was used to calculate our dependent variable: *total number of trips between and within neighborhoods per day*, and two of our explanatory variables: trip distance (i.e., the shortest path between two Bicing stations, considering both bike lanes and bike-friendly streets)

and difference in altitude (i.e., the difference in altitude between the origin and destination stations). We removed any trips with a duration of either less than 60 s (Teixeira & Lopes, 2020) or more than two hours (i.e., the time limit imposed by Bicing to penalize a user). We also ensured that no trip had a speed greater than 50 km/hour, which is Barcelona's speed limit for all vehicles taking the streets within the city boundaries. In addition, we excluded any trips that occurred between the same station and those that were made between 11:00 pm and 5:59 am, as there is minimal Bicing movement during this period. These pre-processing filters resulted in 21,459,722 trips that involved 517 Bicing stations in 62 neighborhoods.

Given that our intention is to analyze the Bicing-user movements across Barcelona, we set our unit of analysis at the neighborhood-dyad level (i.e., neighborhood A to neighborhood B). Although the total number of neighborhood dyads is 3844 ( $62 \times 62$  neighborhoods), not all dyads have at least one trip. Thus, our final sample comprises 3721 dyads for our analysis. We considered both intra- and inter-

**Table 1**  
Variables and measurement.

Variable	Description	Unit	Source	Aggregation
<i><u>Dependent variable</u></i>				
Number of trips between and within neighborhoods	Total number of trips from origin station to destination station for each neighborhood dyad	Count of trips	Bicing	Daily per neighborhood
<i><u>Weather</u></i>				
Wind	Average wind speed	Meters/second	Transparency portal of Catalunya	Daily
Temperature	Average temperature is outside the comfortable range – 1; else – 0	°C	Transparency portal of Catalunya	Daily
Rain	Average amount of precipitation	Millimeters	Transparency portal of Catalunya	Daily
Humidity	Average relative humidity	Percentage	Transparency portal of Catalunya	Daily
<i><u>Nonworking days</u></i>				
Sunday	Sunday – 1; else – 0	Dummy		Daily
Saturday	Saturday – 1; else – 0	Dummy		Daily
Holiday	National and local holiday – 1; else – 0	Dummy		Daily
<i><u>Socio-demographic profile</u></i>				
Income level	Average tax payment in the neighborhood of the origin station	Euros	Open Data BCN	Neighborhood
Population	Number of residents living in the neighborhood of the origin station	Count of people	Open Data BCN	Neighborhood
Males	Percentage of males over the total population in a neighborhood	Percentage	Open Data BCN	Neighborhood
Age	Average age of the residents of the neighborhood of the origin station	Number of years	Open Data BCN	Neighborhood
Academic level	Average highest academic level achieved by the residents of the neighborhood of the origin station (divided into 5 categories from 1 as the lowest to 5 as the highest)	Scale between 1 and 5	Open Data BCN	Neighborhood
<i><u>Land use</u></i>				
Office space (%) – origin	Percentage of office space (including commercial, schools, and universities) over the total available space in the neighborhood of the origin station	Square meters	Open Data BCN	Neighborhood
Office space (%) – destination	Percentage of office space (including commercial, schools, and universities) over the total available space in the neighborhood of the destination station	Square meters	Open Data BCN	Neighborhood
Leisure space (%) – origin	Percentage of leisure space (including parks, museums, theater, and cinemas) over the total available space in the neighborhood of the origin station	Square meters	Open Data BCN	Neighborhood
Leisure space (%) – destination	Percentage of leisure space (including parks, museums, theater, and cinemas) over the total available space in the neighborhood of the destination station	Square meters	Open Data BCN	Neighborhood
<i><u>Trip details</u></i>				
Distance	Shortest amount of distance covered between origin station and destination station (considering both bike lanes and bike-friendly streets)	Meters	Open Data BCN & Bicing	Neighborhood
Altitude	Difference in altitude between origin station and destination station	Meters	Open Data BCN & Bicing	Neighborhood
<i><u>Infrastructure</u></i>				
Public transport availability	Number of nearby bus and metro stations within 250 m of buffer radius of the origin station	Count of transport alternatives	Open Data BCN	Neighborhood
Bike-friendly streets	Amount of bike-friendly streets within 250 m of buffer radius between the origin station and destination station	Meters	Open Data BCN	Neighborhood
Bike lanes	Amount of bike lanes within 250 m of buffer radius between the origin station and destination station	Meters	Open Data BCN	Neighborhood
Bicing availability	Number of nearby Bicing stations within 250 m of buffer radius of the origin station	Count of stations	Open Data BCN	Neighborhood

neighborhood trips that occurred between 2019 and 2020. To account for the days in which Bicing was closed operations due to government-imposed lockdowns, our sample covered the same time frame from June 24 (the day when the government-imposed restrictions were lifted) to December 31 over both years, yielding a net total of 384 days. Our final number of dyad-day observations for the analysis was 1468,408, covering 13,366,133 user trips.

The second set of data used in the analysis comes from Open Data BCN, an open data portal of the Barcelona City Council which allows access and use of information “for the common good and for the benefit of anyone and any entity interested” (see <https://opendata-ajuntament.barcelona.cat/en/open-data-bcn>). From this data source, we extracted information about the built environment of the city (i.e., the transport infrastructure including Bicing’s docking-station layout and characteristics, other transport stations, bike lanes, and bike-friendly streets), the socio-demographic profile of the neighborhood residents (e.g., population, age, academic level, and income level), and the land use of the spaces through the cadastral distribution of each neighborhood. Finally, we obtained the weather conditions (e.g., rainfall, temperature, humidity, and wind) from the Transparency Portal of Catalunya (see <https://transparencia.catalunya.cat> for further details), the open data repository managed by the Generalitat de Catalunya.

ps://analisi.transperenciacatalunya.cat for further details), the open data repository managed by the Generalitat de Catalunya.

### 3.3. Analysis

In our analysis, we performed probabilistic machine learning in a quasi-experimental research design to predict the likelihood of Bicing usage against a set of variables including the trip characteristics, type of day (working or nonworking), infrastructure, weather, socio-demographic profile of the neighborhood residents, and land use of the neighborhoods. We used a hierarchical model to account for the different sources of variation in the daily recorded trips. There are two sources of variation in our analysis: daily (i.e., day-to-day changes in Bicing usage) and dyad (i.e., difference in Bicing usage from an origin to a destination neighborhood) variables. More details on the measurement of the variables can be found in Table 1.

The daily variation includes weather conditions (i.e., wind, temperature, rain, and humidity measures averaged by location according to the closest weather station to the corresponding Bicing station) and nonworking days (i.e., holidays and weekends). The dyad variation

includes all the factors that explain why some neighborhoods have high or low baseline number of Bicing trips. We grouped them into four categories: trip details, infrastructure, socio-demographic profile of the neighborhood residents, and land use of the neighborhoods.

Trip details involved the average trip distance between Bicing stations within or across neighborhoods and the average difference in altitude between the origin and destination stations. Infrastructure consisted of four variables: bike lanes (i.e., the total length in meters of the constructed bike lanes between two Bicing stations), bike availability (i.e., the number of other Bicing stations close to the origin Bicing station), bike-friendly streets (i.e., the total length in meter of the streets with a maximum speed of 30 km/hour for vehicles), and public transport availability (i.e., the number of bus and metro stations close to the origin Bicing station). All the infrastructure variables are computed using a buffer offset of 250 m to consider the alternate path options for the trip between the origin and destination stations (c.f., [Faghih-Imani, Eluru, El-Geneidy, Rabbat & Haq, 2014](#); [Kabak, Erbaş, Çetinkaya & Özceylan, 2018](#); see also [Appendix A](#) for more details of the computation).

The socio-demographic profile included the characteristics of the residents of the origin neighborhood, such as income level (i.e., average annual income tax of the household), population (i.e., total number of residents), males (i.e., percentage of male residents as a proportion of the total number of residents), age (i.e., average age of the residents), and academic level (i.e., average highest educational attainment of the residents). Land use was captured using the cadastral distribution of the properties in the neighborhood, specifically by measuring the office and leisure spaces as a percentage of the total available space. We included the land use for both the origin and destination Bicing stations in the model to distinguish the profile of the user and the possible motive of the trip.

Apart from the different sources of variation in our analysis, another reason for using a hierarchical model specification is our substantive interest in the differences in behavior between the two time periods considered, namely pre-COVID and COVID. Therefore, we allowed all parameters to vary between the two time periods but also assume that they come from the same hyperparameter. By doing so, we could ensure that the resulting pre-period parameter differences are caused by differential behavior emerging from the analysis of the user-trip data and not a product of statistical chance.

Our analytical model is a negative binomial regression with effects estimated partially pooling two time periods (p). Since we expect unequal variance in the distribution of our dataset, we believe that a negative binomial is better suited for our analysis than Poisson that restricts the mean and assumes the variance to be equal. Our model below contains the explanatory variables ( $\beta_p$ ) at the daily level, varying intercepts on the n2n (neighborhood-to-neighborhood) dyads ( $\delta_{n2n,p}$ ) explained by the dyad variation ( $\theta_p$ ), and the difference in infrastructure between the periods ( $\gamma$ ). We also accounted for the overdispersion of the dyads ( $\alpha_{n2n}$ ). Given the complexity of the model, we employed machine learning algorithms using probabilistic programming through Bayesian inference in PyMC3 ([Salvatier, Wiecki & Fonnesbeck, 2016](#)). Below is our full model specification, which is robust to a different specification using lognormal and multiple varieties of negative binomial models (see [Appendix B](#)).

$\text{Trips}_{n2n,t} \sim$	$NB(\mu_{n2n,t}, \alpha_{n2n})$	- Main data component
$\mu_{n2n,t} =$	$\exp(\delta_{n2n,p} + \beta_p XD_t)$	- Day-to-day linear factors
$\delta_{n2n,p} =$	$\theta_p XN + \gamma_p DI, \sigma_\delta$	- Neighborhood-to neighborhood linear factors
$\beta_p \sim$	$N(\mu_\beta, \sigma_\beta)$	- Prior for day-to-day parameters
$\theta_p \sim$	$N(\mu_\theta, \sigma_\theta)$	- Prior for neighborhood parameters
$\gamma \sim$	$N(0, 1)$	- Prior for infrastructure differences parameters
$\sigma_\delta, \sigma_\theta, \sigma_\beta \sim$	$N(0, 1) T(0, )$	- Prior for the standard deviation, truncated
$\log(\alpha_{n2n}) \sim$	$N(\mu_\alpha, \sigma_\alpha)$	- Prior for overdispersion

Where:

● n2n:

(continued)

	Neighborhood-to-neighborhood (origin to destination), unit of analysis, dyad
● t:	Time in days
● p:	Time period (either pre- or post-COVID)
● XD:	Variables at the day-to-day level
● XN:	Variables at the neighborhood level
● DI:	Difference in cycling infrastructure (between pre- and post-COVID)
● $\beta_p$ :	Vector of effects of day-to-day variables
● $\theta_p$ :	Vector of effects of neighborhood-to-neighborhood variables
● $\gamma$ :	Effects of infrastructure difference (pre- and post-COVID)

## 4. Findings

### 4.1. Descriptive statistics

[Table 2](#) presents the descriptive statistics of our dataset. Overall, the total Bicing usage for the covered period of our analysis (i.e., June 24 to December 31 of 2019 and 2020) increased from 6363,597 trips before the pandemic to 7002,536 trips during COVID-19. [Fig. 2](#) shows the evolution of the total daily Bicing trips within and between the neighborhoods of Barcelona. The trends between the two periods are similar, where the peaks of the trip waves are on working days while the troughs are on nonworking days. We also observe that a relatively low number of trips that occurred in both years are during the summer months of July and August and the December holiday season. Moreover, Bicing movements during 2020 were clearly higher in terms of total daily trips than in 2019. Although the total number of trips was higher in 2020 than in 2019, the average number of daily trips was lower in 2020 than in 2019, which can be attributed to the increase in the number of docking stations covering more neighborhoods of the city in 2020.

The descriptive statistics of most of the explanatory variables either did not change or changed very little between the two periods. The noticeable changes are those related to infrastructure (i.e., bike lanes and bike-friendly streets). The increase in bike-related infrastructure can be attributed to the initiative of the government of Barcelona to implement tactical urbanism by taking advantage of the lockdown to convert many streets into being cyclable and to expand the number and length of bike lanes throughout the city.

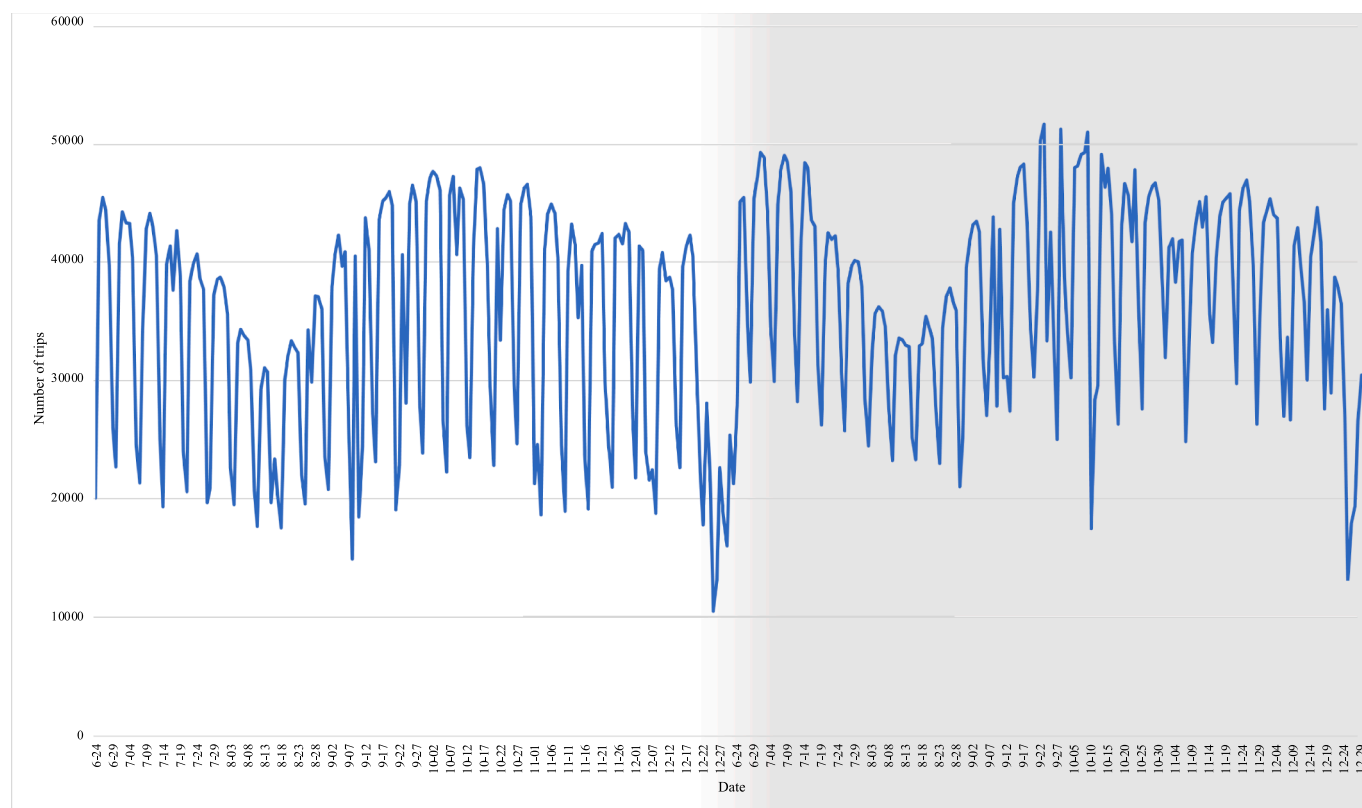
[Fig. 3](#) displays the movement of Bicing trips and the changes in bike-related built infrastructure (i.e., bike lanes and bike-friendly streets) throughout Barcelona as the pandemic unfolded. We observe that bike lanes (the blue lines in the maps) have increased from 2019 to 2020, particularly around the Eixample district. In 2019, bike-friendly streets (the green lines in the maps) were more prominent at the outskirts of the city where Bicing movements were low. After the lockdown in 2020, Barcelona has increased the number of bike-friendly streets by setting a maximum speed limit of 30 km/hour in many streets in highly populated areas of the city, such as the districts of El Raval, Barri Gòtic, and Gràcia. With regard to Bicing trips, the increase in the number can also be observed at many stations as is represented by the circles on the map with their colors darkened in the periods shown.

In the following subsections, we discuss the relevance of several factors on Bicing usage and how such relevance may have changed after the lockdown. We grouped the factors into five sets: trip attributes and type of day, infrastructure, weather, socio-demographic profiles of the neighborhood residents, and land use of the neighborhoods. [Table 3](#) and [Figs. 4 and 5](#) summarize the results, providing the model estimate (in terms of the log of the expected count of trips), the odds, the parameter uncertainty, and the credible intervals for the expected effects. We have standardized all variables, and therefore, the effects that we report are all comparable between them. To interpret the results, one unit increase/decrease in our explanatory variables is equivalent to an increase/decrease in the inter-quartile range. The expected effects of the variables are considered relevant if the probability distribution does not

(continued on next column)

**Table 2**  
Descriptive statistics.

Variable	Pre-COVID		COVID	
	Mean	(s.d.) [interquartile range]	Mean	(s.d.) [interquartile range]
<i>Dependent variable</i>				
Number of trips per neighborhood dyad	11.30	(32.40) [0:8]	9.84	(29.40) [0:6]
<i>Weather</i>				
Wind	2.62	(1.06) [1.95:3.01]	2.56	(1.15) [1.85:2.91]
Temperature	21.10	(5.31) [17.4:25.2]	20.50	(6.01) [15.7:26.1]
Rain	0.11	(0.31) [0:0]	0.06	(0.24) [0:0]
Humidity	63.00	(10.8) [56:71]	63.50	(12.2) [55:71]
<i>Type of day</i>				
Holiday	0.04	(0.20)	0.05	(0.22)
<i>Socio-demographic profile</i>				
Income level	276,000	(191,000) [132,000:384,000]	276,000	(191,000) [132,000:384,000]
Population	22,500	(12,100) [13,500:28,800]	22,700	(12,200) [13,600:29,400]
Males	0.47	(0.02) [0.46:0.48]	0.47	(0.03) [0.46:0.48]
Age	43.70	(2.13) [42.40:45.10]	43.70	(2.15) [42.50:45.20]
Academic level	1.98	(1.36) [0.75:3.28]	1.90	(1.37) [0.75:3.22]
<i>Land use</i>				
Office space (%) – origin	11.80	(7.94) [8:14]	11.90	(7.89) [8:14]
Office space (%) – destination	11.80	(7.90) [8:14]	11.80	(7.85) [8:14]
Leisure space (%) – origin	10.30	(3.43) [8:12]	10.30	(3.42) [8:12]
Leisure space (%) – destination	10.30	(3.42) [8:12]	10.30	(3.41) [8:12]
<i>Trip details</i>				
Distance	4130	(2150) [2430:5620]	4140	(2150) [2440:5620]
Altitude	−0.26	(50.80) [−32.80:32.00]	−0.22	(51) [−33.00:32.40]
<i>Infrastructure</i>				
Public transport availability	7.28	(2.33) [5.77:8.91]	7.28	(2.33) [5.77:8.91]
Bike-friendly streets	2.56	(1.54) [1.32:3.47]	4.11	(1.64) [2.95:5.06]
Bike lanes	1.64	(0.90) [0.92:2.31]	1.83	(1.08) [0.98:2.58]
Bicing availability	1.55	(0.51) [1.00:1.88]	1.55	(0.51) [1.00:1.88]



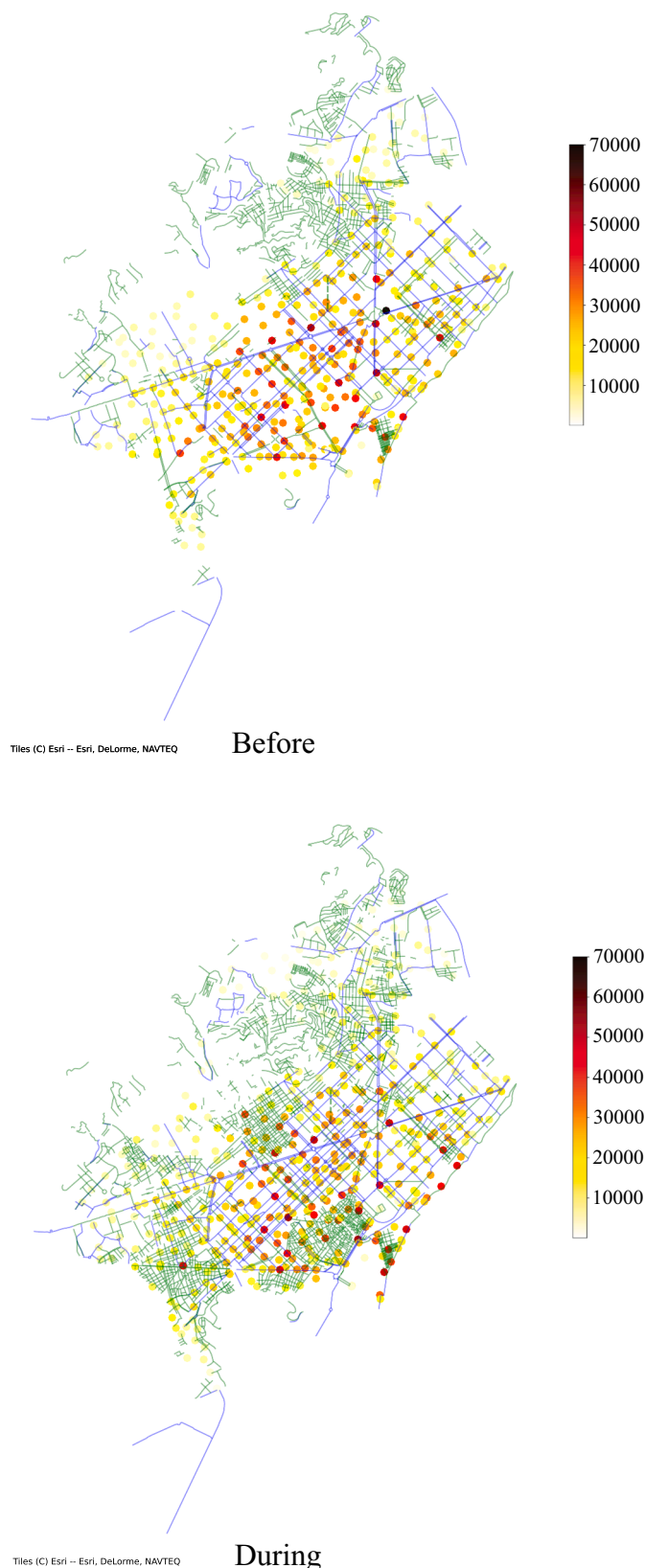
**Fig. 2.** Total number of Bicing trips from June 24 to December 31.

Note: The shaded area in gray shows the COVID-19 period.

fall under a linear effect of zero or an odds ratio of one. The effects are considered to have higher relevance if the linear effect (odds ratio) is farther than zero (one). Fig. 6 displays the effects of the variables in

terms of probabilities, shown on the original ranges of the variables.

- Circle colors show the number of daily trips from the origin station.
- Blue lines are bike lanes; Green lines are bike-friendly streets.



**Fig. 3.** Bicing trips and bike-related infrastructure before and during COVID-19.

Notes:

- Circles represent the bike stations throughout Barcelona.

#### 4.2. The influence of trip attributes and type of day

The distance of the trip has the highest relevant effect on the usage of Bicing. An increase in trip distance (recall that we are using standardized values, and hence it is equivalent to one inter-quartile range) decreases the likelihood of trips by 95.75% (equivalent to a multiplicative effect of 0.042 in odds ratios, or an expected effect of  $-3.159$  in the log of the count of trips). This effect is quite similar before and after the lockdown (95.75 vs. 95.50% respectively). This finding follows the published main objective of Bicing, which is targeted at short trips to complement the city's existing public transportation system. Thus, our study supports previous research that shows evidence of a negative relationship between distance and bike trips (e.g., Ma et al., 2020; Simons et al., 2013; Wang & Lindsey, 2019).

In a similar vein, the difference in altitude between the origin and destination of a trip has a negative relationship on the number of trips (e.g., Bordagaray, dell'Olio, Fonzone & Ibeas, 2016; Hood, Sall & Charlton, 2011; Lu, Scott & Dalumpines, 2018). Although this is still substantial when compared with the rest of the variables, the effect of the difference in altitude is much less relevant than trip distance. An increase in altitude (again, one inter-quartile range) reduces the number of trips before the lockdown by  $\exp(-0.787) = 0.455$  times or  $1 - 0.455 = 54.5\%$  and by  $36.7\%$  ( $\exp(-0.457) = 0.633$  times) after the lockdown. This finding implies that individuals are much less likely to consider altitude as a barrier to using Bicing during a pandemic. This might be explained by Bicing users preferring to overcome any difference in altitude between stations during the pandemic to avoid using other crowded means of transportation.

With regard to the type of day, as expected, most Bicing trips occur during working days (e.g., El-Assi, Mahmoud & Habib, 2017; Wang & Lindsey, 2019). Bicing trips on weekends (i.e., Saturday and Sunday) and holidays (both national and local levels) were about 50% less likely to occur than during working days (i.e., Monday to Friday). The lack of Bicing movement during holidays and weekends is consistent with previous research suggesting that Barcelona residents are less likely to move during these days (e.g., Graells-Garrido, Serra-Burriel, Rowe, Cucchiatti & Reyes, 2021). However, during the pandemic, the relevance of the negative influence of weekends and holidays on Bicing usage has decreased by around 40%, likely due to the increased demand for leisure/recreational activities (c.f., Albuquerque et al., 2021). Again, we observe a differential mobility behavior pre- and post-lockdown.

#### 4.3. Infrastructure

As Barcelona has engaged in tactical urbanism to increase bike-related infrastructure (i.e., bike lanes and bike stations) throughout the city during the pandemic, we find that bike-related infrastructure is mostly relevant to predict Bicing usage. We first looked at each overall effect of bike lanes and cyclable streets, and then at the quasi-experimental effect of increasing such infrastructure before and after the lockdown. Our findings show that an increase in the amount of bike lanes between Bicing stations multiplies the number of trips by 5.48 and 2.87 before and after the lockdown, respectively. Although there is a decrease in the relevance of the effect of bike lanes on BSS usage during the global pandemic, this may be attributed to the dispersed expansion of bike lanes throughout the city in the same period.

However, our analysis also reveals that the total amount of bike-friendly streets between stations is negatively associated with the number of Bicing trips. An increase in bike-friendly streets between Bicing stations is associated with 49.34% fewer trips before and 8.61% fewer trips during the pandemic. A likely reason for this negative relationship is that Barcelona first began converting bike-friendly streets in

**Table 3**

Effects of trip details and seasonality, infrastructure, weather, and socio-demographic variables on bike-sharing usage before and during COVID.

Variables	Pre-COVID					COVID				
	Mean	Odds	s.d.	HPD 2.5%	97.5%	Mean	Odds	s.d.	HPD 2.5%	97.5%
<u>Weather</u>										
Wind	−0.048	0.953	0.001	−0.050	−0.047	−0.048	0.953	0.001	−0.050	−0.047
Temperature	−0.110	0.895	0.001	−0.112	−0.108	−0.091	0.913	0.001	−0.093	−0.089
Rain	−0.272	0.761	0.001	−0.275	−0.270	−0.206	0.813	0.001	−0.208	−0.203
Humidity	−0.053	0.948	0.001	−0.055	−0.052	0.006	1.006	0.001	0.005	0.007
<u>Type of day</u>										
Sunday	−0.605	0.546	0.001	−0.607	−0.602	−0.383	0.682	0.001	−0.385	−0.380
Saturday	−0.432	0.649	0.001	−0.435	−0.430	−0.231	0.794	0.001	−0.233	−0.229
Holiday	−0.519	0.595	0.002	−0.524	−0.515	−0.313	0.731	0.002	−0.317	−0.309
<u>Socio-demographic profile</u>										
Income level	0.913	2.492	0.075	0.766	1.034	0.792	2.208	0.059	0.685	0.910
Population	−0.068	0.934	0.085	−0.202	0.094	−0.064	0.938	0.059	−0.145	0.053
Males	0.435	1.545	0.054	−0.284	−0.073	0.357	1.429	0.054	−0.615	−0.397
Age	0.449	1.567	0.065	−0.038	0.190	0.076	1.079	0.057	−0.153	0.069
Academic level	0.066	1.068	0.046	0.391	0.568	−0.055	0.946	0.050	0.380	0.572
<u>Land use</u>										
Office space (%) – origin	0.477	1.611	0.037	0.260	0.398	0.480	1.616	0.039	0.217	0.379
Office space (%) – destination	0.330	1.391	0.072	0.308	0.587	0.299	1.348	0.088	0.214	0.518
Leisure space (%) – origin	−0.180	0.835	0.038	0.437	0.589	−0.499	0.607	0.044	0.159	0.318
Leisure space (%) – destination	0.516	1.675	0.060	0.328	0.557	0.232	1.261	0.056	−0.033	0.190
<u>Trip details</u>										
Distance	−3.159	0.042	0.040	−3.239	−3.087	−3.100	0.045	0.040	−3.177	−3.022
Altitude	−0.787	0.455	0.044	−0.870	−0.702	−0.457	0.633	0.041	−0.536	−0.379
<u>Infrastructure</u>										
Public transport availability	−0.160	0.852	0.049	−0.254	−0.069	−0.031	0.969	0.039	−0.108	0.051
Bike-friendly streets	−0.680	0.507	0.055	−0.785	−0.580	−0.090	0.914	0.053	−0.177	0.017
Bike lanes	1.869	6.482	0.053	1.766	1.973	1.353	3.869	0.044	1.271	1.441
Bicing availability	1.280	3.597	0.072	1.134	1.404	0.857	2.356	0.065	0.731	0.965

the outskirts of the city where few Bicing trips occur before converting streets in the city center where the highest concentrations of Bicing trips take place. It is also important to note that the relevance of this negative relationship has diminished and fallen into the uncertainty range during the global pandemic, thus implying an increase in the use of Bicing after the lockdown.

When accounting for the aggregate difference in bike-related built infrastructure (i.e., bike lanes and bike-friendly streets), we find that an increase in bike-related built infrastructure between stations increases the number of trips by 1.88 times. Such a finding is extremely relevant because it not only emphasizes the relevance of bike-related infrastructure but also highlights that the changes in infrastructure (which include those related to tactical urbanism) have a direct, immediate, and short-term impact (c.f., [El-Assi et al., 2017](#); [Wang, Akar & Chen, 2018](#)). Therefore, we uncover evidence to support the effectiveness of rapidly changing the city infrastructure to increase Bicing usage.

Our findings also show that a higher availability of Bicing stations increases the number of trips by 2.60 times before and 1.36 times during the pandemic. The decrease in the relevance of this factor can be attributed to a probable lag effect of installing new docking stations (c.f., [Basu & Ferreira, 2021](#); [Bian et al., 2021](#); [Xu & Chow, 2020](#)), many of which were installed to expand Bicing's operational area rather than increasing their concentration in popular locations. In contrast, we find support for prior research suggesting that the availability of other modes of transport (i.e., buses and metros) is associated with fewer Bicing trips ([Braun et al., 2016](#)). However, the effect is barely relevant, with an increase in public transportation availability reducing the number of Bicing trips by 14.79% before and 3.05% during the pandemic. This finding suggests that Bicing may not necessarily be used to fulfill the “first or last mile” of the trip (c.f., [Shaheen & Chan, 2016](#); [Zhang, Qian & Bian, 2019](#)). The lack of relevance of the effect of alternative public transport availability may be attributed to the tendency of the community during the pandemic to avoid modes of public transport that are prone to congestion and involve close contact with other people, thus increasing the possible use of Bicing as a substitute for other transport

modes for mobility around the city.

Overall, these findings confirm the importance of bike-related infrastructure in increasing the likelihood of Bicing usage (e.g., [Habib, Mann, Mahmoud & Weiss, 2014](#); [Pedroso, Angriman, Bellows & Taylor, 2016](#); [Schoner & Levinson, 2014](#)) by highlighting their importance relative to other factors such as weather, the socio-demographic profiles of neighborhood residents, and neighborhood land use.

#### 4.4. Weather

Since many previous studies provide evidence of the significant relationship between weather and bike usage (e.g., [El-Assi et al., 2017](#); [Eren & Uz, 2020](#); [Sears, Flynn, Aultman-Hall & Dana, 2012](#)), we also examined the relevance of weather conditions (i.e., rain, temperature, wind, and humidity) in Barcelona to predict the number of Bicing trips. Among the weather variables, our findings show that rain has the most relevant effect on Bicing usage. An increase in rainfall reduces the number of trips by 23.82% and 18.62% (before and after the lockdown, respectively). This finding is consistent with the extant research that shows the negative association between bike usage and the amount of rainfall (e.g., [Corcoran, Li, Rohde, Charles-Edwards & Mateo-Babiano, 2014](#); [Gebhart & Noland, 2014](#); [Kim, 2018](#); [Mattson & Godavarthy, 2017](#)). The slight decrease in relevance of the effect of rainfall is consistent with [Wang and Noland's \(2021\)](#) findings, where they posit that the effect of rainfall on BSS usage has tended to reduce during the global pandemic.

We also find noticeable effects of temperature, wind, and humidity, albeit with weak relevance. When the temperature goes beyond comfort levels (below 14° and above 29 °Celsius), Bicing trips decrease by 10.42% and 8.70% before and during the pandemic, respectively. Wind reduces Bicing trips by 4.69% both before and after the lockdown. However, humidity, while decreasing Bicing trips by 5.16% before the lockdown, reversed its effect and increased trips by 0.60% during the pandemic. The weak relevance of the relationships between certain weather variables and Bicing usage can be attributed to the minimal

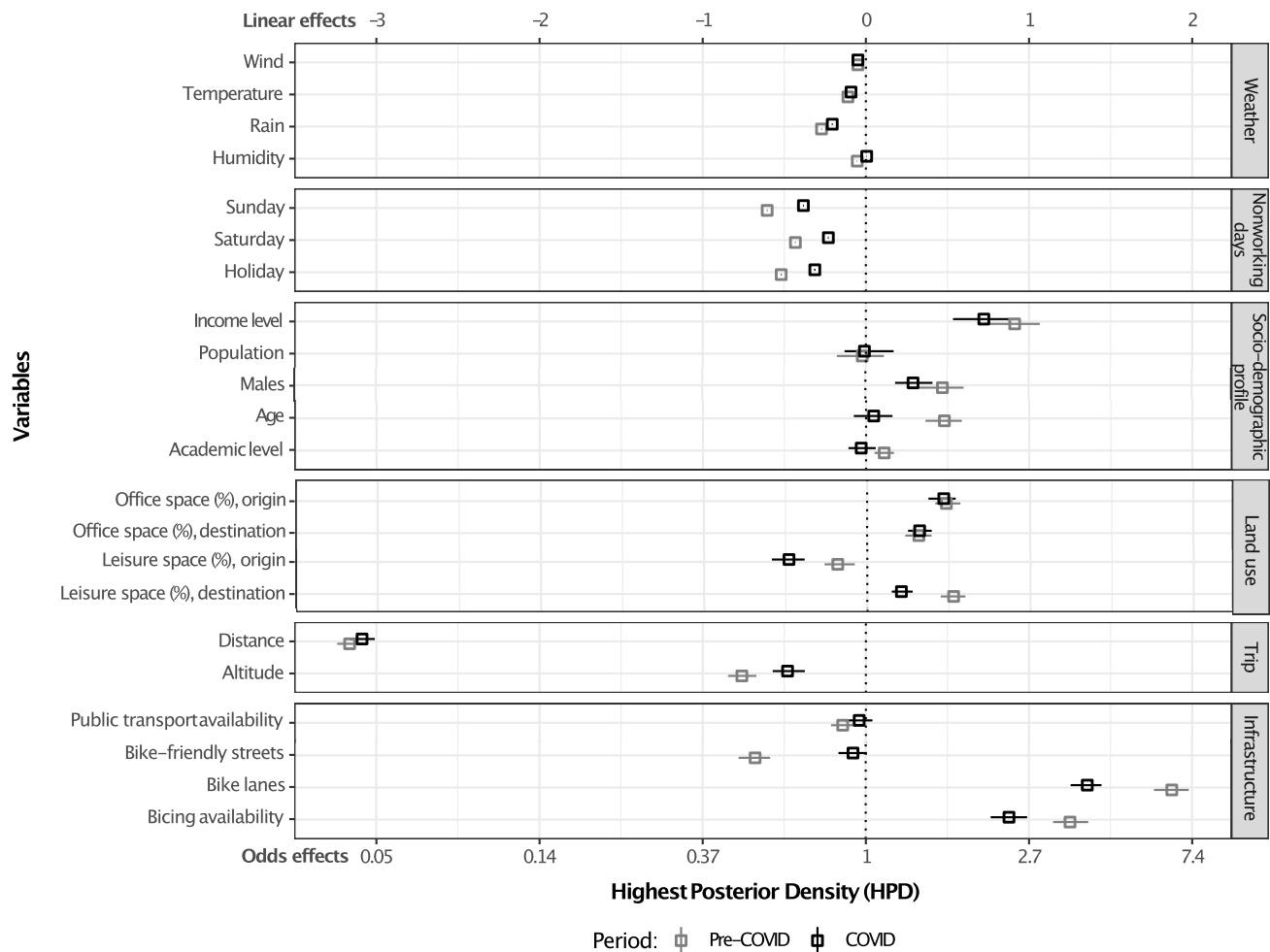


Fig. 4. Coefficient plot of the linear and odds effects of variables on Bicing usage.

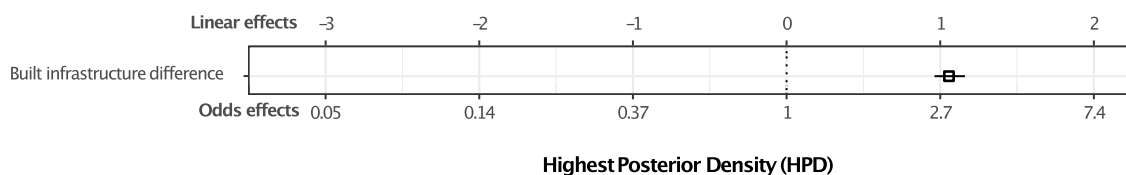


Fig. 5. Linear and odds effects of infrastructure change on Bicing usage.

difference in the weather conditions of Barcelona. The changes in temperature, wind, and humidity around the city have a relatively narrow range throughout the year. Thus, with the exception of the amount of rainfall, our findings show that the weather variables have a relatively weak relevance on determining Bicing usage, both before and after the lockdown periods.

#### 4.5. Socio-demographic profile of the neighborhood residents

The literature on BSS also emphasizes the importance of analyzing the socio-demographic characteristics of the bike-sharing users (e.g., Feng & Li, 2016; Willberg et al., 2021). In this study, we find that most of socio-demographic variables included in our analysis have relatively weak relevance in influencing the number of Bicing trips. Among this set of variables, the total population and academic level seem to have the least relevance, with their effects falling into the uncertainty range. These results show evidence suggesting that the total population of the neighborhood and the academic level of the residents are not relevant in

predicting Bicing usage, which contradicts previous research showing a positive significant effect of population and academic level on bike usage (e.g., El-Assi et al., 2017; Wang & Lindsey, 2019; Zhang, Thomas, Brussel & Van Maarseveen, 2017). A possible explanation for our findings is that Bicing usage is prevalent across the neighborhoods of Barcelona, regardless of the population size.

The influence of age and gender on the number of Bicing trips is more relevant than population size and academic level, although their effects have changed in different ways before and after the lockdown. Before the pandemic, age was expected to increase Bicing usage by 56.67% and males were expected to account for a 54.50% increase. These findings show that neighborhoods with an older and higher proportion of males in their population are likely to make more Bicing trips than those neighborhoods with younger and lower percentage of male population (e.g., Fishman, Washington & Haworth, 2014; Ricci, 2015). After the lockdown, the relevance of the effect of gender on Bicing usage slightly decreased (42.90% more usage where the male population increases by one inter-quartile range), but age barely has any relevant effect

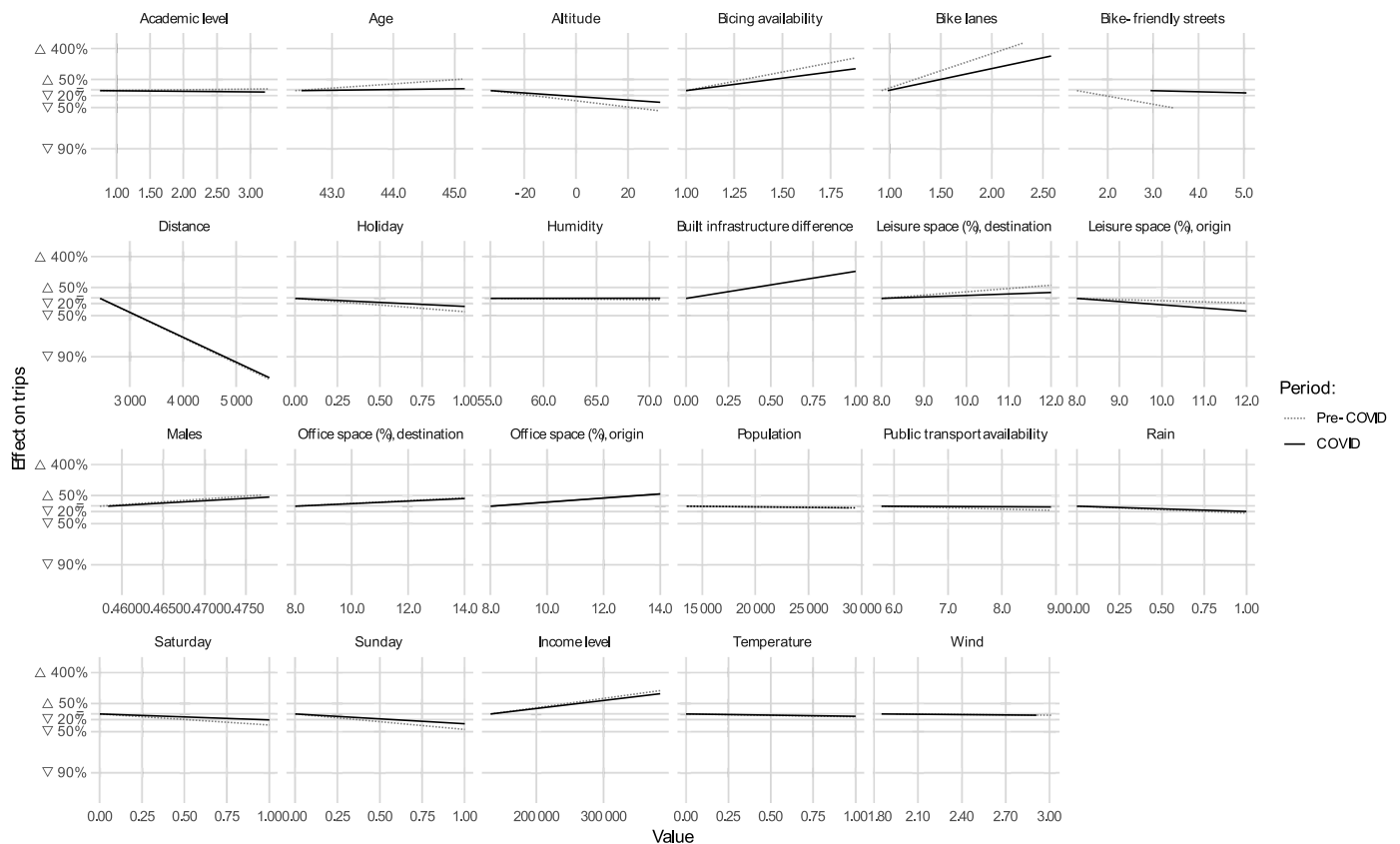


Fig. 6. Percentage effects of linear and odds effects of variables on Bicing usage.

anymore. These results suggest that neighborhoods with a higher percentage of women have increased their use of Bicing and that Bicing usage seemed to occur across various neighborhoods with different age structures as the global pandemic unfolded.

Income level appears to have the highest relevance on usage among the socio-demographic profile of neighborhood residents. A unit increase in its inter-quartile range increases the number of trips by 149.18% (almost 1.5 times increase) before and 120.78% (or 1.2 times increase) after the lockdown. This finding shows that neighborhoods with residents who have a higher average income level are likely to make more trips than those neighborhoods with lower average income level (e.g., Fishman et al., 2015). The decrease in the relevance of this factor during the pandemic may be due to an increase in Bicing usage by commuters from lower-income neighborhoods.

#### 4.6. Land use of neighborhoods

As we accounted for the land use of the spaces in the neighborhoods, we find that a higher number of office space increases Bicing usage by 61.12% and 39.10% for the origin and destination neighborhoods before the pandemic, respectively. These effects have barely moved after the lockdown. This relationship is consistent with higher Bicing usage during working days than weekends and holidays, since it may be possible that many users take Bicing to go to work. This finding highlights the importance of Bicing as means of transportation for the day-to-day activities of city residents for work reasons (Xing, Wang & Lu, 2020).

When we analyzed the relevance of the percentage of leisure spaces in the neighborhoods, the effect diverges depending on whether it pertains to the origin or destination neighborhood. On the one hand, an increase in leisure spaces in the origin neighborhood decreases the number of Bicing trips by 16.47% and 39.29% (before and after lockdown, respectively). This negative effect and the increase in the

relevance of the effect diverge from previous research suggesting that cycling during the pandemic is primarily for leisure purposes (Kim, 2021; Nguyen & Pojani, 2022). However, our findings support the conjecture that BSS usage may be more likely be for work-related motives, rather than for leisure-related activities (e.g., El-Assi et al., 2017; Kabak et al., 2018; Kaltenbrunner, Meza, Grivolla, Codina & Banchs, 2010; Rixey, 2013; Wang et al., 2018).

On the other hand, an increase in spaces for leisure in the destination neighborhood increases the number of Bicing trips before and during the pandemic by 67.53% and 26.11%, respectively. A likely explanation for this positive relationship is the proximity of many docking stations to leisure spaces and bike lanes. Given that docking stations are typically concentrated in neighborhoods with a high percentage of office spaces, and users primarily take Bicing for work-related purposes, finding available spots to return bikes is easier in leisure rather than in office areas. The decrease in the relevance of the positive effect of this variable may be attributed to a spillover effect of the lockdown in which working from home continues to be prevalent among firms, thus reducing Bicing movement around neighborhoods with a high percentage of leisure spaces. In addition, although there has been an increase in the use of parks and green spaces during the pandemic, residents may choose to access these spaces by walking instead of using BSS (c.f., Venter, Barton, Gundersen, Figari & Nowell, 2020).

#### 5. Discussion and conclusion

Despite the effects that COVID-19 has had on urban mobility in general, we find that the aggregate number of Bicing trips has increased after the lockdown, compared to the same time period before the pandemic. Although the extant literature provides evidence of the significant relationship between several sets of factors and BSS ridership, our findings suggest that not all factors are highly relevant in considering the predicted use of Bicing. We also find that the onset of COVID-

19 has mostly reduced the relevance of how a comprehensive set of factors influence the use of Bicing. The most notable factors that consistently have high relevant effects on Bicing usage both before and during the pandemic are bike-related built infrastructure, trip distance, and the income levels of neighborhood residents.

### 5.1. Research implications

Our study has several important implications for research on BSS. First, much of the extant research on BSS analyzes the effect of numerous factors. As a result, previous studies offer rich empirical evidence regarding the significant influence of trip characteristics, built infrastructure, weather conditions, the socio-demographic profiles of the users, and land use of the city on BSS ridership. Despite the significant relationships found in the literature, we still lack a full understanding of the factors that are relevant in predicting the use of BSS in cities. Therefore, our study specifically addresses this research gap by investigating the relevance of the effect of a comprehensive set of factors to determine BSS usage. Although our findings mostly mirror the extant research in suggesting the significant effect of the factors used in our analysis, we ultimately identified that increasing bike-related infrastructure (e.g., tactical urbanism), trip distance, and the income levels of neighborhoods are the most relevant predictors of BSS ridership in Barcelona.

Second, the emergence of the concept of tactical urbanism as a tool for cities to implement temporary, rapid, and low-cost changes in their urban environments has also generated growing academic interest. The scholarly dialog has already shifted from the debate regarding the acceptability of the concept (c.f., Silva, 2016)—to denote actions previously referred to as guerilla urbanism, pop-up urbanism, and D.I.Y. urbanism, among others (Lydon, Bartman, Garcia, Preston & Woudstra, 2012)—toward understanding the characteristics, mechanisms, and effectiveness of adopting tactical urbanism (e.g., Cariello, Ferorelli & Rotondo, 2021; Graziano, 2021; Stevens, Awepuga & Dovey, 2021). Our study explicitly engages with this literature by analyzing the relevance of increasing bike-related built infrastructure, which Barcelona has used as a strategy for implementing tactical urbanism, to incentivize active mobility in the city. By doing so, we uncover the effectiveness of the program, as we find that the adoption of tactical urbanism is highly relevant in predicting the use of BSS as the global pandemic unfolded.

Third, a large body of research relies on survey data to capture the collective behavior of bike-sharing users, while some researchers gather information through observations and experiments in selected locations. These types of data collection are limited in capturing the big picture of mobility in an entire city. We thus follow a growing number of studies that employ a big data approach in analyzing the usage of bike-sharing systems (e.g., Chibwe et al., 2021; Shang et al., 2021; Teixeira & Lopes, 2020). The advantage of using information from BSS-user trips allows us to make conjectures based on real-world data analysis of the whole population of interest, rather than as a product of sample respondent perception or statistical chance. Analyzing large datasets has high statistical power that typically results in highlighting significant relationships. Our analysis in this study allows us to determine which factors yield relevant relationships, which may be important to focus on during transport mobility design and planning. We do so by combining different sources of variation with a high level of precision by accounting for the effects of variables at the day-to-day level (i.e., weather conditions) and at the neighborhood level (i.e., trip characteristics, infrastructure, the socio-demographic profiles of the residents, and land use of the neighborhood spaces). Thus, our approach and findings may be useful for future research to better understand the factors that are relevant to predict BSS usage.

Fourth, our investigation compares two time periods that directly preceded and followed an exogenous shock (i.e., COVID-19) that disrupted transport-system operations and societal behavior (e.g., Hu et al., 2021). Our approach helped us determine whether the relevance of the

factors that affect BSS ridership may have changed as the global pandemic unfolded. We ultimately found that COVID-19 has generally reduced the relevance of the effect of the factors that predict the use of BSS in Barcelona. Moreover, given that we also intended to examine the effectiveness of tactical urbanism, our quasi-experimental research design allows us to quantify the effect of infrastructural changes. Although the COVID-19 lockdown was common in all neighborhoods, the treatment received in terms of improvements of bike-related built infrastructure was not shared across neighborhoods. Therefore, we can assess the precise effect of the infrastructure changes once the system has reopened after the lockdown. Understanding how COVID-19 has affected the use of BSS can be crucial, not only for researchers to understand the impact of disruptive events on the mobility of urban communities, but also for policymakers responsible for the preparations, management, and resilience of cities with respect to future disruptive events (c.f., Sharifi & Khavarian-Garmsir, 2020).

### 5.2. Practical implications

Our findings are also important for Bicing managers and policy-makers to help establish sustainable programs that can incentivize the use of BSS (c.f., Leister, Vairo, Sims & Bopp, 2018). In particular, we uncover evidence of the effectiveness of the city's implementation of tactical urbanism during the pandemic, as the influence of the changes in the bike-related built infrastructure in increasing Bicing usage throughout the city is highly relevant. Since one of the main barriers to bike usage is the threat to personal safety (e.g., Fishman et al., 2013; Pedroso et al., 2016; Yao & Wu, 2012), further increasing and integrating bike lanes and bike-friendly streets could encourage citizens to use Bicing more extensively.

Moreover, given that our findings suggest that long distance and low-income level also have highly relevant effects on reducing the number of trips, another prospective approach to encourage Bicing usage is to increase the number of electric bikes available and/or reduce the price of their usage. On the one hand, electric bikes help to increase cycling among a wider range of the user population because they require less effort than regular bikes, particularly for trips with long distance and high difference in altitude between the origin and destination stations (Simsekoglu & Klöckner, 2019).

On the other hand, Bicing's current pricing model is targeted at short trips, probably dissuading some citizens with a lower capacity to pay to use it because the price over longer-distance trips would be close to the price of transport alternatives (c.f., Simons et al., 2013). Since commuters with higher income are more likely to use BSS (Fishman et al., 2015), one potential way to incentivize those commuters at a lower-income range to use the service is to reduce the prices of Bicing. A price reduction can empower the groups facing socioeconomic barriers to consider Bicing as an alternative transport mode, thus contributing to closing the social equity gap concerning BSS while promoting active mobility in general (c.f., Chen & Li, 2021; Desjardins, Higgins & Páez, 2022; Lee, Sener & Jones, 2017).

Furthermore, we observed that many neighborhoods with lower levels of income had experienced an improvement of bike-related infrastructure (including the implementation of tactical urbanism) during the pandemic, resulting in a noticeable increase in BSS usage. This finding may suggest the role of the city's infrastructure in narrowing the social equity gap regarding BSS usage (c.f., Braun, 2021; Firth, Hosford & Winters, 2021). Researchers already provide evidence of the disparity in access to bike-related infrastructure, in which disadvantaged groups had significantly lower access to bike lanes than others (Braun, Rodriguez & Gordon-Larsen, 2019; Hirsch, Green, Peterson, Rodriguez & Gordon-Larsen, 2017; Mora, Truffello & Oyarzún, 2021). Thus, we urge the city planners to include social equity principles in developing the spatial distribution of bike-related infrastructure to promote active mobility across all neighborhoods.

### 5.3. Limitations and avenues for future research

Despite the strengths of our extensive data and quasi-experimental research design, our study is limited to a single context and therefore suffers from a threat to its external validity. Future research should explore how our findings hold in other comparable contexts with similar conditions to Barcelona. For example, although Bicing began operations in 2007, Barcelona can still be considered at an early stage of maturity with regard to cycling culture, compared to very mature cities (e.g., Amsterdam, Copenhagen, Helsinki, and Paris) with residents who are likely to use bikes as their primary mode of urban mobility. Thus, studies that examine a maturing city in terms of cycling culture would be useful.

In addition, our analysis has not accounted for the socio-demographic profiles of the actual users of the BSS in Barcelona, due to the city's strict enforcement of regulations that protect the identity and privacy of users. Notwithstanding, we follow previous studies with a similar approach in using the profiles of neighborhood residents to capture the collective behavior of the community (e.g., Braun et al., 2016; Faghih-Imani, Hampshire, Marla & Eluru, 2017; Hu et al., 2021). We therefore urge future studies to include actual user characteristics to determine the preferences and motivations underlying the use of BSS.

Finally, it is likely that other factors excluded from our analysis may influence BSS ridership in Barcelona. Specifically, several Bicing substitutes such as private bikes, dockless BSS, and shared electric scooters and motorcycles have also increased in popularity among the city residents after the lockdown. In a similar vein, the movements of private vehicles were not accounted for in our analysis. Future research understanding how these alternative modes of transport affect the use of BSS can offer a more complete picture of the relevant factors to predict BSS ridership.

### 5.4. Conclusion

Barcelona aims to significantly contribute to achieving the UN's

Sustainable Development Goals, and as a result become one of the most sustainable cities in the world. To achieve these aims, it has implemented several urban-development programs that promote sustainability, including the expansion of its BSS (i.e., Bicing) and associated bike-related infrastructure to incentivize clean and active mobility throughout the city. Taking advantage of the disruption that COVID-19 had on urban mobility, Barcelona has engaged in tactical urbanism through a series of rapid infrastructural changes to address the abrupt shift in societal behavior that has taken place in the city. In this study, we analyzed how a comprehensive set of factors influenced the use of Bicing before and after the COVID-19 lockdown in Barcelona, identified the relevant factors that help predict Bicing usage, and unpacked how the relevance of these factors changed as the global pandemic unfolded. Ultimately, we uncovered evidence of the effectiveness of tactical urbanism in riding the wave of the global pandemic.

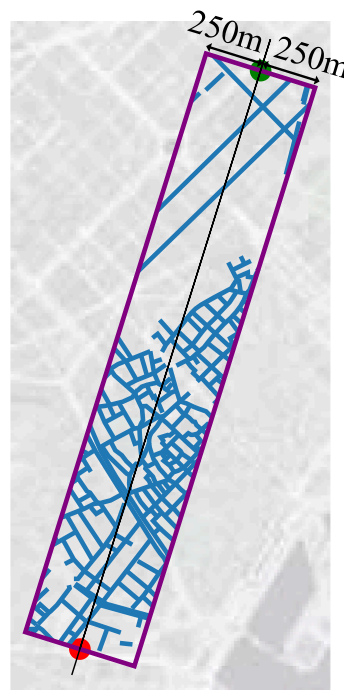
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### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

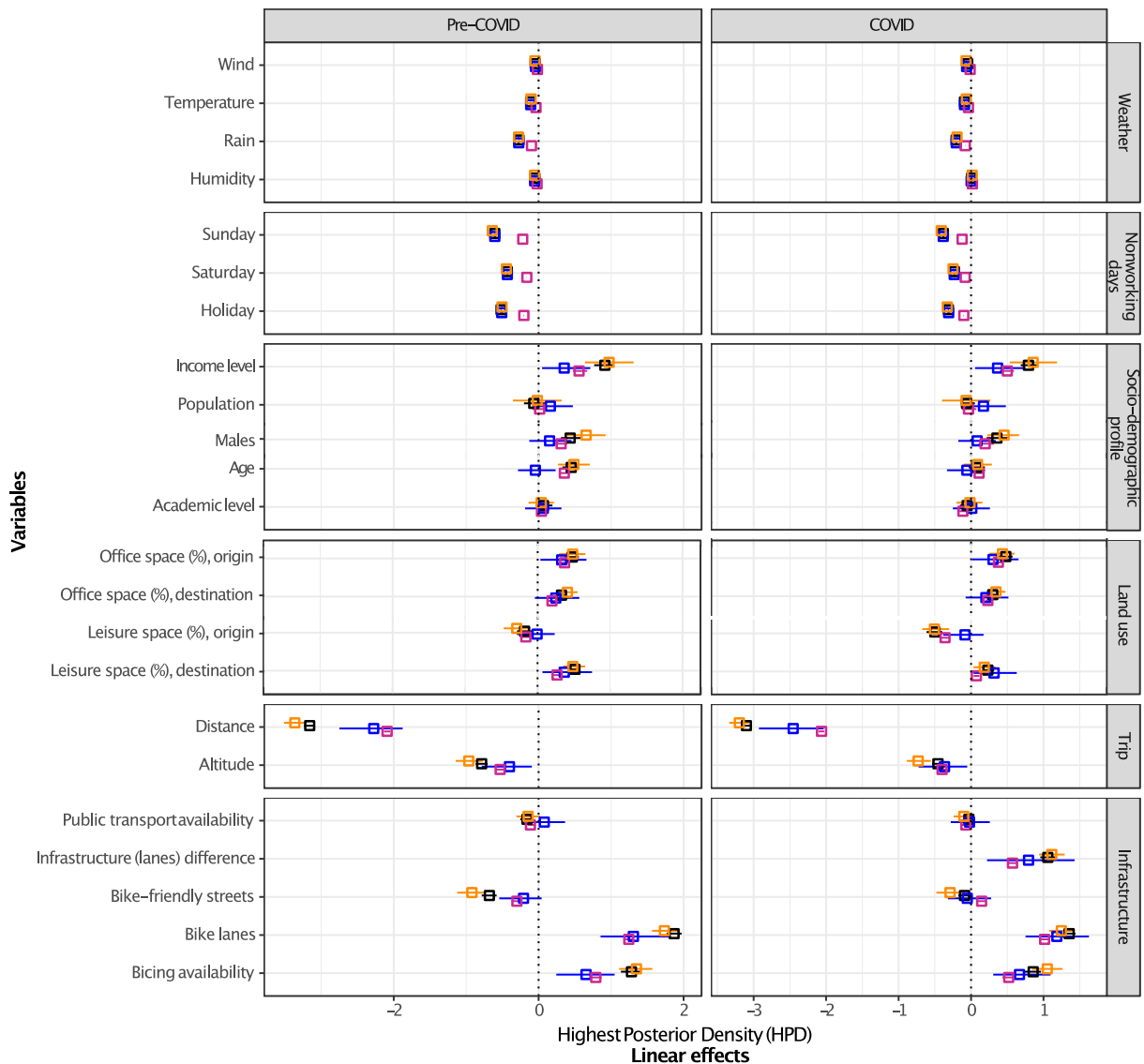
## Appendix A: Sample computation of bike-related infrastructure



## Notes:

- Circles in green and red are the origin and destination stations, respectively.
- The blue lines are the bike paths and bike-friendly streets for the trip path within a 250-meter buffer (in purple box).

## Appendix B: Robustness check using various model specifications



Model/Method: ■ Lognormal/Metropolis ■ Negative Binomial/ADVIbs=10k ■ Negative Binomial/Metropolis ■ Negative Binomial/NUTS (40%g, 30%g)

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